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ABSTRACT

A diametral extensometer was developed and employed during temperature ramp tests with the Fuel Cladding Transient Tester (FCTT). Plastic strain measurements were performed using unirradiated 20% cold-worked AISI 316 stainless steel tubing ramped at 5.6 and 111C$^{\circ}$*/s with internal pressures from 3.4 to 93.1 MPa. Results demonstrated that plastic deformation can occur at stresses well below the conventional 0.2% yield strength and that most deformation in such tests occurs in the final 50C*$^{\circ}$ *before failure.*

Postirradiation tests were performed on fuel pin cladding irradiated to 5.8 x 10^{22} *n/cm*^{2} *(E>0.1 MeV) with irradiation temperatures to 540*$^{\circ}$*C. The tests showed that, for test pressures of 17.2 MPa or less, the stress-strain behavior was unchanged from unirradiated material behavior although the strains at failure were greatly decreased.*

INTRODUCTION

Cladding mechanical property data for analysis and prediction of fuel pin transient behavior were obtained under experimental conditions in which the temperature ramps of reactor transients were simulated using the Fuel Cladding Transient Tester (FCTT).(1-4) The FCTT tests were performed by internally pressurizing sections of tubing and subjecting them to a constantly increasing temperature with an induction coil until the specimens ruptured. The pressure remains relatively constant throughout the test, since the volume of gas inside the specimen is connected by a capillary tube to a larger volume of gas which remained at room temperature.

FCTT tests prior to this work yielded failure strength and ductility data as a function of temperature. Results of postirradiation tests have shown a pronounced loss of cladding strength and ductility, which is termed the "fuel adjacency effect."(5) These data are useful in demonstrating conservatism of fast reactor cladding temperature integrity limits and demonstrating the similarity of cladding behavior between in-reactor and out-of-reactor simulated transient tests.(4)

Recently, a diametral extensometer was developed to continuously measure the specimen diameter during an FCTT test. The extensometer measures the specimen diameter at two orthogonal orientations by contacting the specimen with fused silica probes. These probes were attached to elastic hinges which actuated linear variable differential transformer (LVDT) position sensors. A high-speed microprocessor is used to record the extensometer output and sample temperature and pressure during the test. The system was installed in a hot-cell and tests were conducted on unirradiated and irradiated cladding.

Data from the extensometer will be used in mechanistic fuel pin performance codes to model flow behavior of fuel pin cladding during reactor transient events.

DATA REDUCTION METHODS

Due to the transient temperature conditions, the extensometer diameter measurements must be corrected for the thermal expansion and temperature dependence of the elastic modulus to yield cladding plastic strain values. The corrections for the specimen diameter change due to the temperature dependence of the elastic modulus were based on Nuclear Systems Materials Handbook(6) values and the data of Gibbes and Wyatt,(7) which were fit with the equations:

$$\ln\ln\left(\frac{E^*}{E}\right) = 0.87056 - \frac{1928.23}{T} \qquad (1)$$

for $T \leq 1043\text{K}$

$$\ln\ln\left(\frac{E^*}{E}\right) = 3.2399 - \frac{4400.3}{T} \qquad (2)$$

for $T \geq 1043\text{K}$

where $E^* = 28 \times 10^6$ psi,
E = elastic modulus, and
T = temperature, K.

The temperature dependence of Poisson's ratio taken from the Nuclear Systems Materials Handbook(6) was:

$$\nu = 0.24279 + 7.6784 \times 10^{-5}T \qquad (3)$$

where ν = Poisson's ratio, and
T = temperature, K.

The thermal expansion of the unirradiated 20% C.W. 316 stainless steel tubing was measured with the extensometer from 370 to 1300°C. A least squares fit to the data yielded the equation:

$$\Delta D_T,\% = 0.7702 + 2.3611 \times 10^{-3}T - 4.4263 \times 10^{-7}T^2 + 1.8636 \times 10^{-10}T^3 \qquad (4)$$

where $\Delta D_T,\%$ = percent thermal expansion, and
T = temperature, K.

The standard error of estimate of the equation fit to the measured data was 0.028% or 1.6 μm. The comparison of the thermal expansion given by Eq. (4) with published TPRC(8) values shows that the average difference is only 0.010%. The current measurements also extend the available thermal expansion data to a higher temperature.

The corrections described above were used in the following manner to obtain plastic strain:

$$\varepsilon_{\text{plastic}} = \varepsilon_{\text{total}} - \varepsilon_{\text{thermal}} - \varepsilon_{\text{elastic}} \qquad (5)$$

UNIRRADIATED SPECIMEN RESULTS

Transient tests on unirradiated 20% C.W. 316 cladding were performed with the extensometer at 5.6 and 111C°/s. Constant gas pressures ranging from 3.4 to 93.1 MPa produced deformation information from 370 to 1230°C.

Test parameters and results are given in Tables I and II; the results are presented as temperatures during the heating ramps at which specific plastic strain levels (extensometer measurements minus thermal expansion and elastic strain) were reached. Also given are the temperatures and strains at failure; the failure strain is the uniform strain determined from post-test diameter measurements along the entire specimen length at two angular orientations 90° apart. The breach location was not included in the measurements.

The cladding plastic strain results at 5.6C°/s are presented in Figure 1 as a function of temperature for the various pressures employed. The solid curves, representing the cladding plastic strain at a particular constant pressure, demonstrate how the majority of the deformation occurred in the last 50°C preceding failure. Also, the strain rate increased with temperature during each test. Included in each figure is a correlation of the uniform diametral failure strain obtained by micrometer measurement adjacent to the failure site on the specimen after the test. The deformation at the faster rate, 111C°/s, was similar to that at 5.6C°/s except a higher temperature was required to produce the same amount of plastic strain as shown in Figure 2.

These results demonstrate that appreciable deformation can occur during a transient at stresses much less than the conventional 0.2% strain yield strength value; e.g., from 650 to 925°C the stress to produce 0.05% strain decreased from 70 to only 22% of the conventional yield strength value. This result indicates that a cladding deformation model employing only elastic behavior up to the conventional yield strength will not calculate plastic strain which is actually occurring.

IRRADIATED SPECIMEN RESULTS

Tests were also conducted on cladding specimens from irradiated fuel pins. These specimens had a fast fluence of 4 to 6 x 10^{22} n/cm^2(E>0.1 MeV) and irradiation temperatures of 380 to 540°C.

The elastic modulus was measured on three irradiated cladding specimens and found to average 10% less than the unirradiated material modulus. Below 850°C the thermal expansion measurements on one irradiated specimen were identical to unirradiated material. Between 850 and 980°C the expansion of the irradiated specimen was approximately 0.05% less than that for the unirradiated cladding specimen.

The deformation results of irradiated fuel pin cladding tests at 5.6C°/s are given in Table III and compared with unirradiated cladding stress-strain behavior in Figure 3. At temperatures above 750°C, the plastic strain of the irradiated material closely matched that of unirradiated material. However, at lower temperatures, less pressure was required than in unirradiated specimens to produce the same amount of strain. Analysis is still underway to determine the cause of this apparent softening of the cladding stress-strain behavior at lower temperatures. Additionally, future analysis will be directed toward mathematical correlation of plastic strain as a function of temperature, strain rate, and irradiation parameters. The correlation will utilize the Hart equation-of-state approach used previously in the FCTT failure correlation(3) and will also incorporate available pertinent tensile test results.

IMPLICATIONS TO THE FUEL ADJACENCY EFFECT

Cladding specimens taken from the fuel column region of fuel pins have shown a pronounced strength and ductility decrease during certain FCTT test conditions.(2,5) The cladding deformation behavior may account for some of the features of this fuel adjacency effect (FAE). The fact that appreciable plastic strain levels of 0.05% occur at stresses less that one-half the conventional yield strength clarifies how radiation-embrittled cladding with a ductility of 0.05% can fail at stresses well below the conventional yield strength.

The apparent softening of irradiated cladding below 750°C would allow the cladding strain to reach the requisite failure strain at even a lower stress than for unirradiated material, which corresponds with the maximum in the FAE exhibited in this region. Thus, both decreased ductility and a lower stress required to achieve that ductility compound to produce the FAE. At higher temperatures (>750°C) the irradiated claddin deformation behavior is not different, so that the strength degradation results only from the decreased ductility. Consequently, at the higher temperatures the FAE is also less pronounced.

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TABLE I

RESULTS OF 5.6C°/s TRANSIENT HEATING TESTS ON UNIRRADIATED 20% C.W. 316 STAINLESS STEEL

Specimen	Test Pressure, MPa	Temperature for Indicated Plastic Strain During Transient Heating					Uniform* Failure Strain,%	Failure Temperature, °C
		0.05%	0.2%	0.5%	1.0%	2.0%		
		°C	°C	°C	°C	°C		
N-30	3.5	910	1116	1173	1202	1229	8.55	1276
N-28	5.2	839	1003	1079	1117	1146	9.70	1193
N-35	6.9	832	988	1036	1063	1088	7.34	1148
N-34	10.3	783	954	999	1015	1030	5.08	1082
N-33	13.8	766	927	985	999	1008	13.60	1036
N-4	17.2	738	871	949	968	979	2.43	998
N-32	20.7	749	857	924	956	977	3.65	992
N-31	27.6	754	833	877	903	923	4.60	939
N-29	34.5	729	782	823	853	873	6.82	898
N-8	41.4	671	744	782	812	832	2.60	846
N-26	48.3	668	738	767	786	803	4.43	816
N-25	55.2	657	721	749	766	780	3.00	783
N-24	62.1	624	704	733	747	754	2.52	757
N-23	69.0	597	673	704	709	-	1.26	715
N-22	75.8	577	654	685	-	-	1.04	694
N-21	82.7	513	606	-	-	-	0.65	626
N-20	89.6	460	566	-	-	-	0.43	576
N-18	93.1	<371**	538	-	-	-	0.61	577

* Average specimen strain from post-test measurements away from breach location.

** Pressurization at 371°C caused 0.07% plastic strain.

TABLE II

RESULTS OF 111C$^{\circ}$/s TRANSIENT HEATING TESTS ON UNIRRADIATED 20% C.W. 316 STAINLESS STEEL

Specimen	Test Pressure, MPa	Temperature for Indicated Plastic Strain During Transient Heating					Uniform* Failure Strain,%	Failure Temperature, °C
		0.05%	0.2%	0.5%	1.0%	2.0%		
		°C	°C	°C	°C			
N-46	13.8	910	1042	1077	1096	-	7.65	1101
N-45	27.6	873	938	985	1018	-	2.61	1018
N-44	41.4	763	828	871	899	921	3.57	921
N-49	55.2	703	767	797	814	-	1.35	814
N-43	69.0	596	703	-	-	-	0.61	729
N-42	84.1	516	652	-	-	-	0.67	664

*Average specimen strain from post-test measurements away from breach location.

TABLE III

RESULTS OF 5.6C°/s TRANSIENT HEATING TESTS ON IRRADIATED 20% C.W. 316 STAINLESS STEEL

Specimen	Test Pressure, MPa	Irr. T. at Failure Site, °C	ϕt at Failure Site, 10^{22}n/cm^2 E>0.1 MeV	Temperature for Indicated Plastic Strain During Transient Heating				Uniform* Failure Strain,%	Failure Temperature,°C
				0.05%	0.2%	0.5%	1.0%		
P-23C-101K-G	3.5	470	5.46	1020	1110	-	-	0.67	1158
P-14-9-K	3.5	542	4.50	1038	1127	-	-	0.67	1165
P-23C-48C-B	6.9	395	4.30	838	993	1043	1071	0.88	1074
P-14-52-K	10.3	511	5.75	792	938	1001	1027	1.00	1036
P-14-72-E	17.2	421	5.10	725	885	942	961	0.86	979
P-14-72-M	17.2	543	4.68	782	906	-	-	0.31	914
P-14-52-F	22.4	432	5.47	696	857	-	-	0.29	858
P-14-20-I	27.6	507	5.73	+	-	-	-	0.06	662
P-14-28-B	41.4	379	3.75	600	-	-	-	0.11	640
P-23C-98JLD-J	41.4	568	1.85	727	793	826	-	0.85	831
P-14-28-H	55.2	525	5.33	446	627	-	-	0.52	661
P-23B-27B-K	69.0	495	4.58	<371**	421	538	-	0.56	589

* Average specimen strain from post-test measurements away from breach location.

** Pressurization at 371°C caused 0.165% plastic strain.

\+ Failure at 662°C with 0.04% extensoleter strain.

Figure 1. Cladding Plastic Strain ~~Data~~ During 5.6 °C/s ([illegible]) Heating Rate

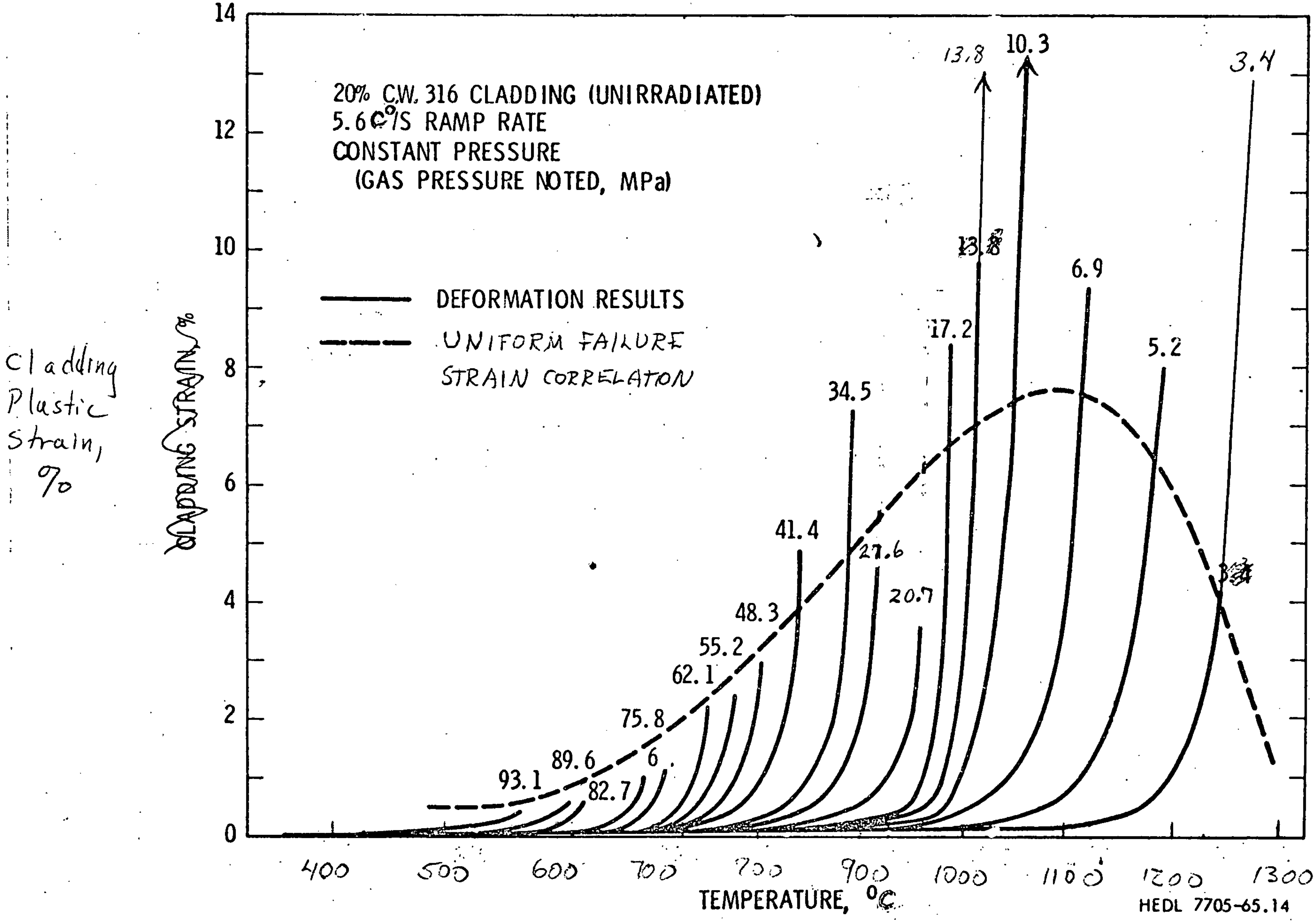


Figure 2. Cladding Plastic Strain During 111 C°/s Heating Rate

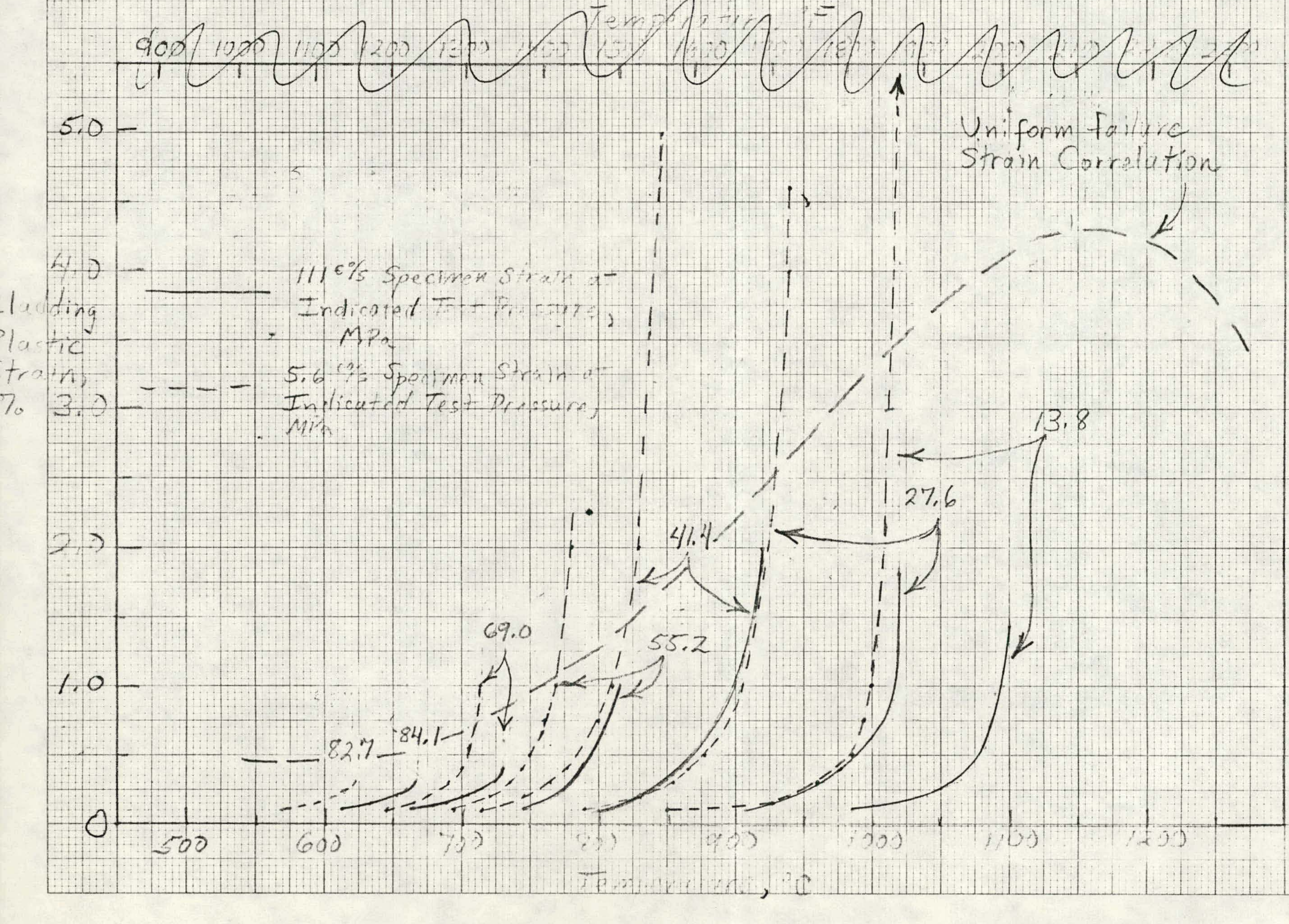
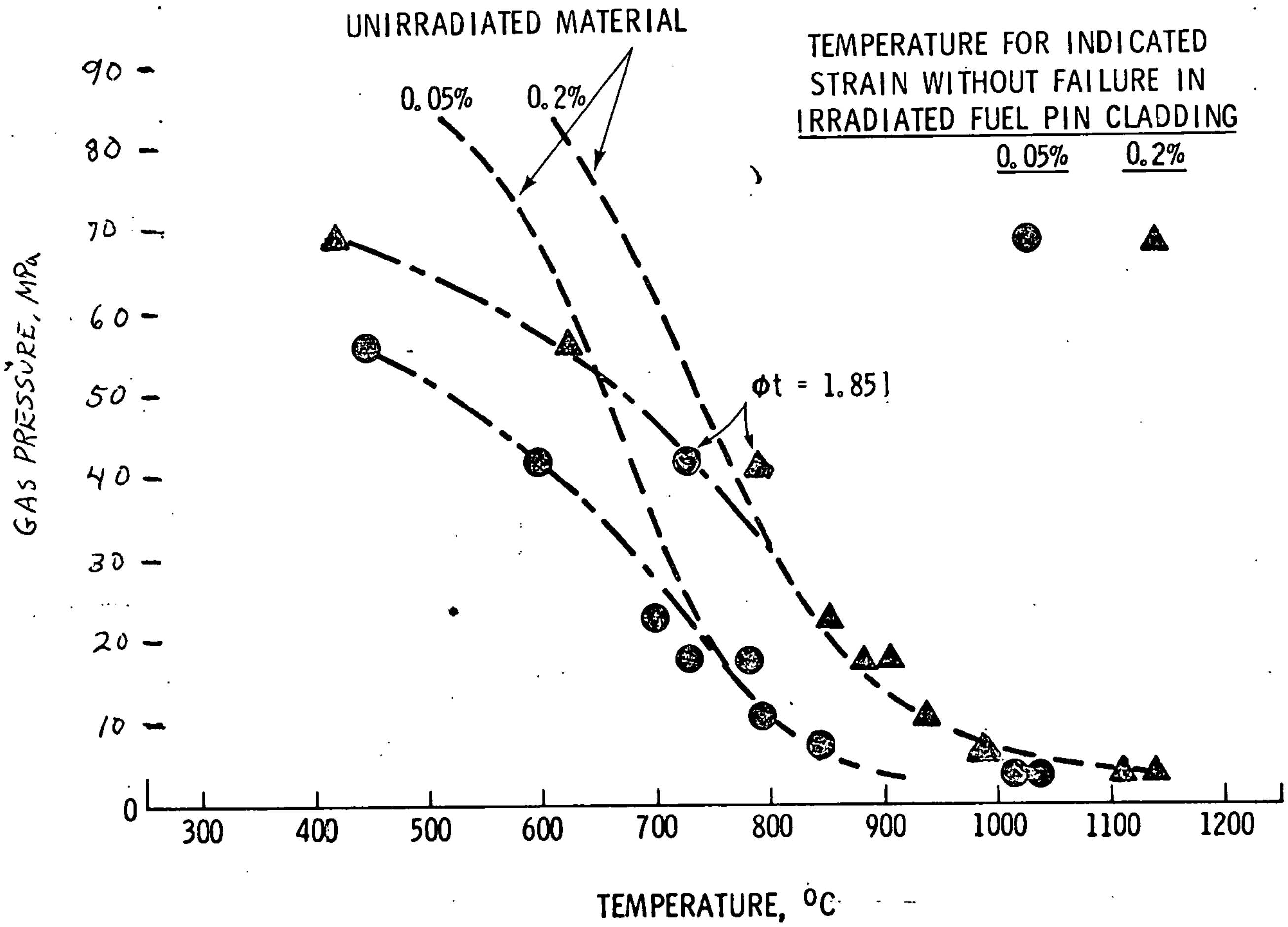


Figure 3. Plastic Strain of Irradiated Fuel Pin Cladding During 5.6 °C/s (10°F/s) Heating Rate
$\phi t = 4$ to 6×10^{22} n/cm² (E>0.1 MeV); Irr. T. ≤ 540°C



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